LCA Case Studies

LCA of Multicrystalline Silicon Photovoltaic Systems

Part 1: Present Situation and Future Perspectives

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Part 1: Present Situation and Future Perspectives • Part 2: Application on an Island Economy

Preamble. This series of two papers which is based on a Diploma Thesis (N. Stylos, 2000) presents the LCA performed for a Multicrystalline Photovoltaic (PV) system and a full scale application on an island. Part 1 presents an energy analysis for all the PV components, extended to the primary energy carriers. In Part 2, a complete and accurate identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed, for an installation of a multicrystalline photovoltaic park on a Greek island.

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Abstract

Aim, Scope and Background. The environmental and energy parameters of Photovoltaic systems play a very important role when compared to conventional power systems. In the present paper, a typical PV-system is analyzed to its elements and an assessment of the material and energy requirements during the production procedures is attempted. An LCA is being performed on the system of production of photovoltaics.

Main Features. An energy analysis is extended to the production of the primary energy carriers. This allows having a complete picture of the life cycle of all the PV-components described in the present study. Four different scenarios are examined in detail providing every possible aspect of scientific interest involving multicrystalline PV systems.

Methods and Tools. In order to obtain concrete results from this study, the specific working tools used are: the energy payback time (EPBT) and the electricity production efficiency (EPE). A process that relates inventory information with relevant concerns about natural resource usage is attempted.

Conlusions. As a final stage of this work, it is assumed that photovoltaics are used in a small island economy, with the hypothesis of a total replacement of the existing conventional power diesel unit. A comparison between the two power systems shows the benefits of an extended use of PV-systems. EPBT and EPE results indicate PV-systems' great potential in producing electricity using limited resources during the several steps of their life cycle.

Recommendation. Technological improvements need to be done in the manufacture of BOS-components which consume during their life cycle almost equal amounts of energy as the photovoltaic modules.

Keywords: Energy pay-backtime (EPE); mc-silicon solar cells; multicrystalline silicon photovoltaic systems; PV-systems; silicon; solar cells

Introduction

Photovoltaic (PV) systems convert light energy directly into electricity. The term 'photo' stems from the Greek 'phos', which means, 'light'. 'Volt' is named after Alessandro Volta (1745–1827), a pioneer in the study of electricity. 'Photovoltaics' could literally mean 'light-electricity' (US DOE Program 1999). Most commonly known as solar cells, PV systems have become very important. 'Solar power' is used as the means of energy for the small calculators and wrist watches. More complicated PV systems provide electricity for pumping water, powering communications equipment, lighting homes and running appliances. In an extensive use of this technology, it is possible to produce a great amount of electricity through large-scale PV systems.

A grid-connected large-scale PV system consists of the photovoltaic modules, the inverters (with all the necessary electronic components), the batteries for the autonomy of the system, and other components such as cables, support structure and foundations (**Fig. 1**) (Seippel 1983, Williams 1986).

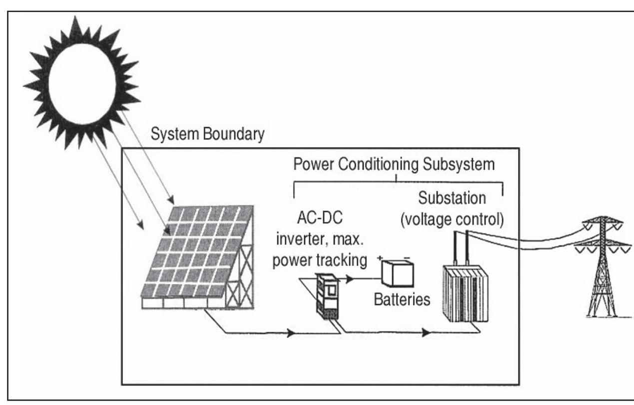

Fig. 1: A large-scale grid-connected PV system schematic calculations have been made on a per module basis

The photovoltaic modules consist of a number of solar cells relevant to the module area. The most important part of a solar cell is the semiconducting layers, where the electron current is created. There are a number of different materials suitable for making these semiconducting layers, and each has benefits and drawbacks. There is not an ideal material for all types of cells and applications. The main types of solar cells are:

1) Multicrystalline silicon cells (mc-Si, also called semi- or polycrystalline silicon)
2) Amorphous silicon cells (a-Si)
3) Cadmium Telluride cells (CdTe)
4) Copper Indium Selenide cells ($CuInSe_2$; also shortened to CIS)

In this study, the life cycle of multicrystalline silicon solar cell modules are analyzed, due to the advantages they present. The most important advantage is that silicon is so readily abundant (it is actually the second most abundant element in the Earth's crust-second only to oxygen). Many PV manufacturers have an extensive research program in the area of multicrystalline silicon solar cells. The objective is to make this kind of cells a beneficial solution for producing electricity.

1 Multicrystalline Silicon Solar Cells

The LCA of a multicrystalline silicon PV module starts with the mining and refining of silica (quartz) (Phylipsen and Alsema 1995). Silica is reduced with the use of carbon and the reduction step is either followed or preceded by a purification step. The resulting high purity silicon is melted and cast into blocks of multicrystalline silicon. The blocks are portioned into ingots (lump of metal, cast in a mould), which are subsequently sliced into wafers. The wafers are processed into solar cells by etching, texture, formation of the emitter layer, application of back surface layer and contacts, passiveness and antireflective coating. The solar cells are tested, interconnected and subsequently encapsulated and framed into modules. All these procedures take place for the manufacture of multicrystalline silicon solar cells.

In this study, four discerned cases are examined, which represent the present and future of PV-technology: the base case, the improved case, the forward case and an application based to the KC-60 PV-module, which is a product of Kyocera Corporation. **Table 1** summarizes the most important tasks, which determine the technological cases.

Table 1: The most important tasks for module fabrication (Phylipsen & Alsema 1995, Lauer 1999)

Process step	Parameter	Base case	Improved case	Forward case	KC-60 case
Silica reduction	Process	Arc furnace	Arc furnace	–	Arc furnace
	Process yield	80%	85%	–	80%
High purity Si production	Process	UCC	UCC	H-p Si reduction with h-p carbon	UCC
	Process yield	96%	98%	80%	96%
Casting / portioning	Casting method	Conventional casting	Improved convent.casting	Electromagnetic casting	Conventional casting
	Contouring losses	14%	11%	6%	14%
Wafering	Wafer size	10 x 10 cm^2	12.5 x 12.5 cm^2	15 x 15 cm^2	10,2 x 10,05 cm^2
	Wafer thickness	300 µm	200 µm	150 µm	300 µm
	Wafering loss	300 µm	200 µm	150 µm	300 µm
Etching / texturing	Sawing damage etchant	NaOH	KOH	NaOH	NaOH
	Texturing			NaOH	
Emitter formation	Doping	$POCl_3$ in diffusion oven	$POCl_3$ in diffusion oven	Screenprinted P in IR oven	$POCl_3$ in diffusion oven
	Emitter back etch	–	HF / HNO_3	–	–
	Edge preparation	CF_4 plasma	CF_4 plasma	Polishing	CF_4 plasma
Metallization	Back contact layer	Screenprinted Al / Ag	Screenprinted Al / Ag	Screenprinted Al	Screenprinted Al / Ag
	Back contact layer thickness	15 µm	10 µm	20 µm	15 µm
	Back side coverage factor	100%	100%	10%	100%
	Front side contact	Screenprinted Ag	Screenprinted Ag	Screenprinted Ag	Screenprinted Ag
	Front contact line width	120 µm	90 µm	50 µm	120 µm
	Front contact thickness	15 µm	10 µm	20 µm	15 µm
	Front side metal coverage	10%	7%	6%	10%
Passivation	Bulk passivation / surface passivation	PECVD of Si_3N_4	PECVD of Si_3N_4	–	PECVD of Si_3N_4
Antireflective coating		in passivation process	in passivation process	CVD of TiO_2	in passivation process
Electr. Testing	yield	95%	95%	95%	95%
Module production	Cells/module	36	36	40	36
	Glass sheet thickness	3 mm	3 mm	3 mm	3 mm
	EVA foil thickness	2 x 0.5 mm	2 x 0.5 mm	2 x 0.25 mm	2 x 0.5 mm
	Tedlar/Al/Te-dlar thickness	125 µm	125 µm	125 µm	125 µm
	Module size (total)	0.44 m^2	0.65 m^2	1 m^2	0.489 m^2
Module testing	Yield	99%	99%	99%	99%
Encapsulated cell efficiency		13%	16%	18%	12.2%
Module life time		30 yr	40 yr	50 yr	30 yr

1 UCC process: a solar-grade silicon purification process based on fluidized-bed technology, developed by the Union Carbide Corporation (UCC)
2 IR oven: acronym for Infra-red oven
3 PECVD: acronym for Plasma Enhanced Chemical Vapour Deposition
4 CVD: acronym for Chemical Vapour Deposition

The base case is chosen in such a way that it represents a good estimate of the present state of production technology and environmental control measures. The improved case is defined as the technology, which will most probably be commercially available within 10 years. The forward case represents an optimistic view on production technology available within the next ten to fifteen years. Finally, KC-60 case is an application of a PV-module, which is already in the market. Thus, comparisons can be made between the previous case studies and some useful conclusions can be drawn.

The process steps (Phylipsen and Alsema 1995) involved in the manufacturing of PV-modules are the following:

(a) For the reduction of silica to silicon is used carbon supplied by charcoal, cokes, low ash coal and wood scrap. The resulting silicon is primarily used in the metallurgical industry and is thus called metallurgical grade silicon. After the reduction of the Si has taken place, oxygen is led through the silicon melt to reduce aluminum and calcium impurities (Wang et al. 1985).

(b) Production of high purity silicon is materialized through the UCC-process, which is a silicon purification process based on fluidized-bed technology. In this process metallurgical grade Silicon (mg-Si) is hydrogenated in a fluidized bed reactor (FBR) at 500°C and 3.5 MPa, at the presence of a copper catalyst (2–4%), producing a mixture of (chloro-)silanes. The components of this mixture are separated by subsequent distillations and in the final distillation step pure silane is separated. Then, silane is pyrolysed in a FBR to solar-grade-silicon (sog-Si) and hydrogen.

(c) Casting process, in which high purity silicon feedstock is converted into large blocks of multicrystalline Si. The presence of impurities and a large number of grain boundaries decrease solar cell efficiencies by facilitating recombination. For this reason, the outer parts of the ingot are removed (contouring) and the ingots are sawed into smaller blocks.

(d) In the wafering process, the silicon blocks are cut into very thin slices. For this purpose a multi wire saw (MWS) is generally used, combined with slurry containing a cooling liquid and some abrasive particles like silicon carbide (SiC). Before processing the wafers into solar cells the sawing damage has to be removed. This can be done by etching with either sodium hydroxide or potassium hydroxide. Subsequently the wafers are rinsed with water and concentrated sulfuric acid.

(e) The n-type emitter layer is formed in the wafer, usually by way of diffusion of phosphorus atoms. After the diffusion step, the edges of the wafers also contain phosphorus atoms. In order to prevent short circuiting, the phosphorus-containing layers are etched off at the edges using a plasma etching process.

(f) In the metallization step, it is assumed that contacts will be applied by screenprinting. A uniform layer of an aluminum and silver containing paste is first screenprinted on the backside of the cell, which provides a Back Surface Field (BSF) preventing recombination of generated electrons and holes. Besides metals (Al and Ag, 70–80%) screenprinting pastes contain solvents, resins, fillers and glass fritt. After the paste has been deposited, the wafers are fired in a belt or infrared oven.

(g) Defects, impurities and grain boundaries in the silicon material can reduce solar cell efficiencies by facilitating recombination of electrons and holes. In the passiveness process hydrogen atoms created in plasma, diffuse into the wafer to inactivate recombination centers (Ruby et al. 1996).

(h) The front surface is yet another facilitator of recombination processes. A surface passiveness layer, like SiO_2 or Si_3N_4, can here reduce the recombination velocity. Usage of a layer of silicon nitride has yet another advantage, since it can also act as an antireflective coating (ARC).

(i) After cell processing the solar cells are tested. The yield of solar cell production is estimated at 95%, i.e. 5% of the tested cells are rejected. The test procedure includes the production test procedure and the reliability test procedure. The production test procedure comprises the visual inspection and structure test, the electrical performance test, the insulation test and the insulation resistance test. Moreover, the reliability test procedure contains the thermal cycle test, the humidity-freeze cycle test, the dump heat test, the heat test, the light exposure test, the salt spray test, the hail impact test, the twist test, the mechanical load test, the static load test, the robustness of terminations test and the impulse voltage test (Lauer 1999).

(j) Subsequently, the remaining cells are encapsulated into a module. The modulation process is similar for the three cases and only module size and other process parameters vary. The tested cells are laid out in a module matrix and interconnected in four series using tin-coated copper strips. The tin layer is applied to enhance the solderability of the strips. The next step is the embedding of the cell matrix in EVA foil. The encapsulation materials consist of a 3 mm thick sheet of chemically hardened glass, 0.5 mm EVA foil, the cell matrix, again 0.5 mm EVA foil and 125 µm Tedlar/Al/Tedlar foil (50 µm aluminum layer). Then lamination takes place at 120–150°C and the edges of the module are sealed with a polysulphide elastomer and the modules are washed and dried. Finally a polyester junction box is attached and the module is framed with an aluminum frame.

1.1 The balance-of-system (BOS) components

The balance of system (BOS) defines the part of the PV power system other than the PV modules. The life cycle of the major BOS elements, which contribute significantly to the inputs and outputs of the entire system, is analyzed. These BOS elements are the inverters (with all the power conditioning electronics), the batteries and the foundations.

It is important to note that the aim was not to analyze and describe the life cycle procedures of the BOS components in detail, but to present the contribution of them to the life cycle of a PV-system. This means that the production procedures of inverters and batteries (except for the steel foundations) has not been studied, but what has been taken into account is the energy inputs and pollutant outputs, through an economic input-output linear model developed by the Green Design Initiative of the Carnegie Mellon University (Green Design Initiative; Consumer Price Indexes). This model allows estimating the overall environmental impacts

Table 2: Main characteristics of the BOS-components

	Inverters		Batteries	
Power (kVA, kW)	300		41,6	
Number of components' replacements	Base case	**0**	Base case	**2**
	Improved case	**0**	Improved case	**3**
	Forward case	**0**	Forward case	**4**
	KC-60 case	**0**	KC-60 case	**2**
Number of units	**3**		**520**	
Life time of PV-system (yr.)	Base case: **30**	Improved case: **40**	Forward case: **50**	KC-60 case: **30**
	Steel foundations			
Type of Steel	ECCS (Electrolytic chrome coated steel)			
Mass of Steel per PV-installation (kg)	Base case	**56229**		
	Improved case	**36167**		
	Forward case	**30140**		
	KC-60 case	**65741**		

and the energy consumption from the manufacture of a certain product, taking into account not only the energy consumption and the impacts of final assembly, but also those from mining of metals, making electronic parts e.t.a. The main characteristics of the analyzed BOS-components, which participate to the PV-cases, are shown in **Table 2**.

From the data in Table 2, it is obvious that only one (1) set of inverters is required during PV-system's life time (Aixon Elektrotechnik GmbH 2000). The installation of batteries is replaced every 10 years. This is a critical point for the study because batteries have a major effect on the system so that the final results change dramatically (Hoppecke Batterien 2000). The mass of steel foundations is changed according to the number of PV-modules in the discerned PV-cases. The smaller the number of PV-modules, the smaller will be the mass of steel required for the construction of steel foundations.

1.2 LCA of photovoltaic systems

The comparison of PV-systems with a conventional mode of electricity production (e.g. diesel unit) can only be adequately done by the use of the LCA methodology. The aim of this photovoltaic study is to determine the environmental burdens (energy and raw material consumption, as well as emissions) caused by the manufacture and operation of a large-scale Photovoltaic system. In order to present the advantages of PV-systems as electricity production units, a comparison of them with a conventional diesel power unit is made. The full scenario includes a large-scale PV installation on a Greek island, which uses Diesel power units to produce electricity.

The functional unit in this study is the number of modules of the PV installation and eventually all calculations have been made on a per module basis.

The number of PV-modules is determined by the energy requirements of the island. The initial calculations for the solar cells have been made on a square meter (m^2) unit solar cell area basis and for the secondary materials (aluminum, glass, EVA, Tedlar) on a per kg unit basis.

Any product or service needs to be represented as a system in the inventory analysis methodology. A system is defined as a collection of materially and energetically connected operations (e.g., manufacturing processes, transport process, or fuel extraction process) which perform some defined function (SETAC Europe 1996).

In the present analysis, the basic elements of the PV-system (**Fig. 2**) are the PV-modules, the inverters, the batteries and the steel foundations. PV-modules, which are the main PV-system's components, are fully analyzed to their materials and a full energy and burdens analysis has been done. However, the materials and production procedures analysis has not been done for inverters and batteries, due to data unavailability. In spite of this, the energy and burdens analysis is also complete for the inverters and batteries through the economic input-output model. On the other hand, the last of the three BOS-elements being analyzed, which is the steel foundations, is fully described and analyzed both for the materials and energy requirements.

As 'various materials' are defined materials like aluminum, steel, copper, zinc and plastics, which are parts of the inverters and batteries but they are not reported in detail.

For the ECCS steel, a full analysis has been done and it is important to note that the modes of transport of the most

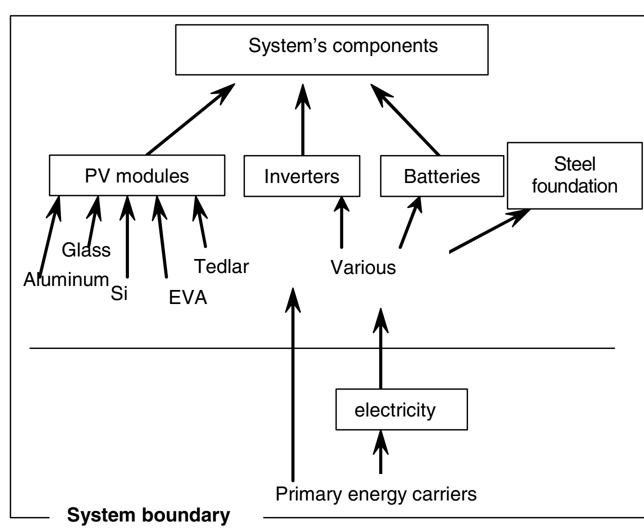

Fig. 2: Basic elements of the grid-connected PV-system with energy storage

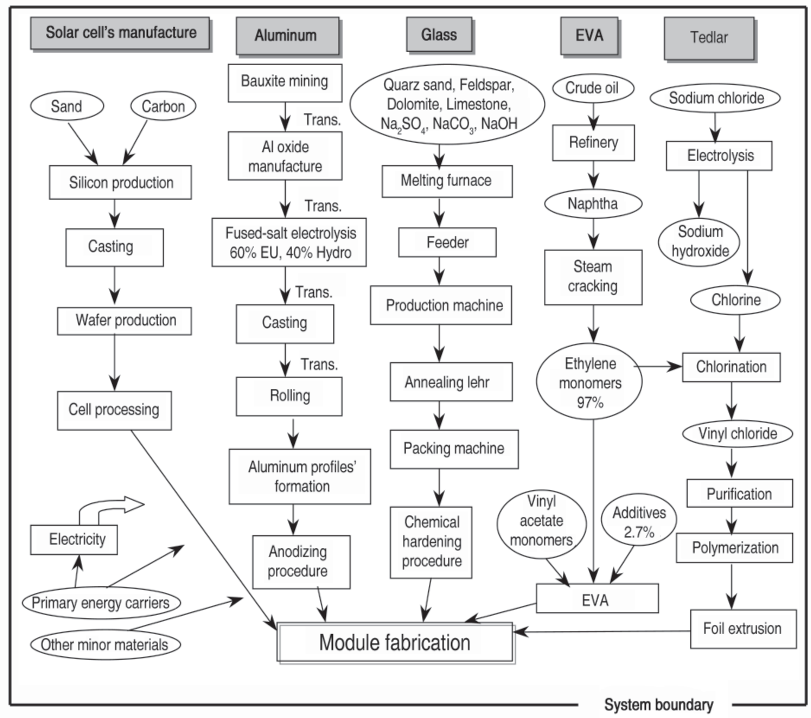

Fig. 3: The system boundaries of energy, material and pollutants flows

important raw materials in the production of the basic PV-module materials (aluminum, glass, EVA, Tedlar, Si) are included in the inventories.The same has also been done for the steel foundations (Swiss Agency for the Environment 1998, The Book of Popular Science 1971, Thermoplastic Material Selection Guide 2000, Typical Properties of Tedlar 2000, Plastic Material Properties 2000).

The module fabrication in its entirety is shown in **Fig. 3**. In this figure, the flow charts of the basic PV-module elements are included. The solar cells' manufacture flow chart originates from the study of 'Environmental life-cycle assessment of multicrystalline silicon solar cell modules' (Phylipsen and Alsema 1995).

The rest of the flow charts are included in the study of Swiss Agency for the Environment, Forests and Landscape (SAEFL) called 'Life Cycle Inventories for Packagings'. In the aluminum and glass flow charts there are a few additions, which are necessary for the completeness of the study. The two last stages in the manufacture of aluminum profiles are not included in the aluminum flow chart of the SAEFL study. Both extrusion of aluminum into profiles and profile anodizing (for enhancing endurability) require an additional amount of energy.

The same occurs with the last stage of glass sheets production, where the production of flat and chemically hardened glass used in solar cell modules requires an additional process energy.

The data needed for the previous process stages are industrial information.

2 PV-System's Characteristics for the Assumed Cases

At this point it is substantial to have a summary picture of the basic characteristics, which determine the different technological cases (see Table 2).

In the first row of **Table 3**, the total installed power of PV-systems for all the PV cases is shown. According to the total installed power and the maximum power of each PV-module the number of PV-modules, which is required for the PV-

Table 3: Technical and energy characteristics of the PV installations on Nisyros island

Parameter	Symbol	Unit	Base case	Improved case	Forward case	KC-60 case
Total installed power	P_{inst}	[kW]	293.28	296.21	296.43	294.12
Number of PV-modules	N_{final}	–	5104	2640	1640	4902
Total PV-module area	A_{mod}	[m^2]	2245.76	1710.72	1640	2397.078
Solar irradiation energy	Π_{irr}	[kWh/m^2·yr]	1797	1797	1797	1797
Intensity of solar radiation (standard)	STC	[kW/m^2]	1	1	1	1
Operation ratio of PV-modules	λ_{mod}	–	0.82	0.82	0.82	0.82
Produced energy DC	E_{DC}	[kWh/yr]	431929.2	436244.41	436568.4	433166.35
System ratio	a	–	0.735	0.735	0.735	0.735
Produced energy AC	E_{AC}	[kWh/yr]	317539.3	320711.62	320949.8	318448.74
Electricity consumption on Nisyros island	E_{Nis}	[kWh/yr]	246050	246050	246050	246050

installation, can be calculated. The total PV-module area can also be calculated by multiplying the number of PV-modules with the area of a single module.

The energy of solar irradiation results by summing the solar irradiation energies of all months of a year, taking place on Nisyros island. Furthermore, the intensity of solar radiation is a standard magnitude, which is equal to 1 kW/m^2 of module area, and is used for describing the technical characteristics of a PV-module. The operation ratio of PV-modules follows from the system ratio multiplyed by the temperature correction factor s_T. This factor is equal to:

$$s_T = 1 - (T_{PV} - T_e),$$

where T_{PV} is the temperature of PV-module and T_e is the temperature of the environment (Kagarakis 1992).

The produced DC energy from the PV-modules results by multiplying the total installed power with the solar irradiation energy, the temperature correction factor and the clearness factor.

The next row of Table 3 provides the system ratio, which is the product of batteries ratio, inverters ratio and wiring ratio. Finally, the produced AC energy is the result of multiplication of the produced DC energy with the system ratio.

3 Final Results and Diagrams

The production of accurate results creates the need for developing metrics to guide improvement of photovoltaic devices and to assess how sustainably these devices generate electricity. The metrics used in the present study, relevant to energy flows of the systems, are the Energy Pay-Back Time (EPBT) and the Electricity Production Efficiency (EPE). The results of these indicators are shown in **Table 4**.

Based on the data of Table 4, **Fig. 4** can be constructed.

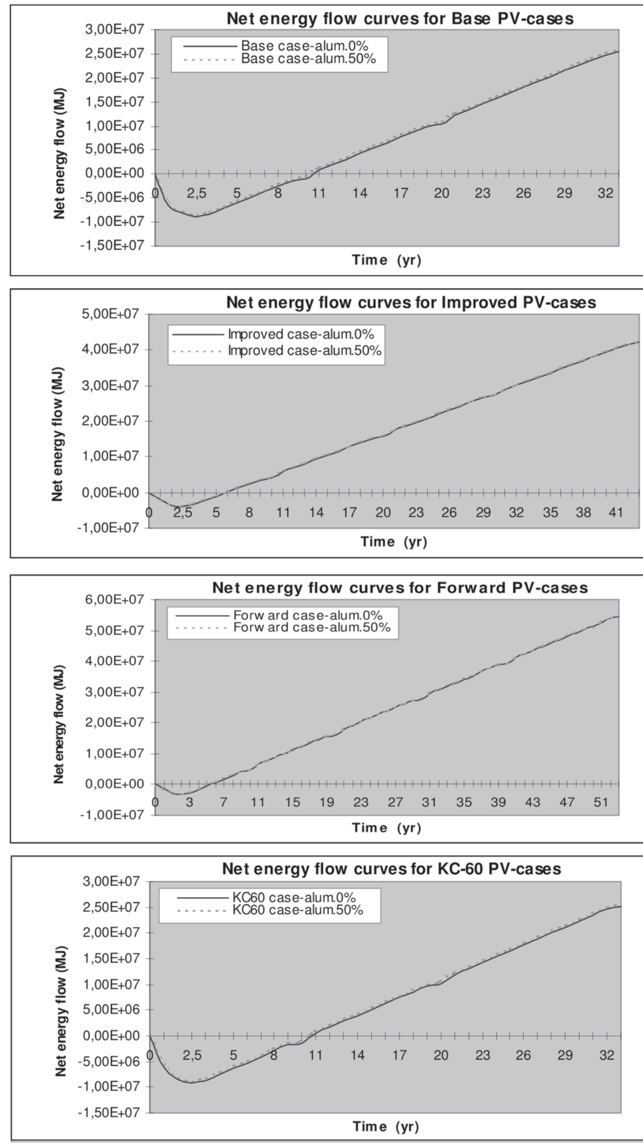

Fig. 4: Diagrams showing the Net energy flows for the discerned PV-cases

Table 4: Results for EPBT and the EPE of the discerned PV-cases

Energy values / Cases		Base case		Improved case		Forward case		KC-60 case	
	Unit	Al 0%	Al 50%	Al 0%	Al 50%	Al 0%	Al 50%	Al 0%	Al 50%
Energy consumption	GJ	10,287	9,784	5,532	5,237	6,167	5,962	10,632	10,161
Energy production per year	GJ/yr	1,143	1,143	1,155	1,154	1,155	1,155	1,146	1,146
EPBT	**yr**	**9.00**	**8.56**	**4.79**	**4.54**	**5.34**	**5.16**	**9.27**	**8.86**
Energy consumption of PV-modules	GJ	4,946	4,443	1,387	1,092	1,151	947	4,970	4,500
Energy consumption-BOS components	GJ	4,600	4,600	4,145	4,145	5,015	5,015	5,662	5,661
Energy production over life time	GJ	34,294	34,294	46,183	46,182	58,000	57,771	34,392	34,392

3.1 Energy Pay-Back Time (EPBT)

Energy Pay-Back Time in years is calculated by dividing the total amount of energy used to manufacture the whole PV-system from raw materials, install and operate it over its life time, and deal with end of life disposition, by the amount of energy the PV-system generates in a year using **Eq. (1)**. The variables in this equation are defined as follows: E_{mat}=energy to extract, process, and transport raw materials to the manufacturing facilities; E_{fab}=energy to fabricate the system's components from raw materials and transport them to the use site; (assumed to be 0); E_{inst}=energy required for PV-system installation; E_{elm}=energy required for any end-of-life management activity (assumed to be 0); $E_{gen/yr}$=energy generated by a PV-system in one year; and $E_{o\&m/yr}$=energy used annually for operation and maintenance (assumed to be 0) (Alsema et al., Lewis and Keoleian 1997).

$$Pay\text{-}Back\,Time = \frac{E_{mat} + E_{fab} + E_{inst} + E_{elm}}{E_{gen/yr} + E_{o\&m/yr}} \quad (1)$$

The PV-system in the base case has a very high EPBT (about 9 yr), which is not a very encouraging fact. It can be seen, from the energy consumption of the PV-modules and the BOS-components separately, that the BOS-components participate with a 50% percentage at the energy consumption of the whole PV-system. In the base case with a usage of 50% recycled aluminum, a reduction of the EPBT of about 5 months can be observed, which is very important.

In the improved case the situation is different, showing the dynamics PV-systems will have in the near future. Total energy requirements will be reduced by 50%, with the electricity production having a slight increase. This will result to a correspondent 50% reduction of EPBT (4.79 & 4.54 yr for the improved case with recycled aluminum 0% and 50% respectively).

Assuming that the technological data concerning BOS-components remain stable, it can be summarized that inverters contribute the same degree to energy consumption, batteries are replaced 3 times instead of 2, in the improved case and steel ECCS contributes according to the discerned cases (the imroved case for steel is used).

Reduction of energy demands in BOS-components is due to the smaller energy requirements of steel foundations, although the energy consumption for the production of batteries is increased.

In the forward case, the capability of reducing the energy demands is limited. On the other hand the forlooking quality of manufacture and durability of the system increases its lifespan up to 50 years. So, in that case EPBT is equal to 5 years and the energy demand for the production of BOS-components will be 5 times greater than those required by the PV-modules.

In KC-60 case, the energy requirements are increased in both PV-modules and BOS-components but this is balanced from the increased electricity production per year from PV-system. However, EPBT of KC-60 is greater than that of the base case.

Moreover, a high use of energy concerning BOS-components can be seen, which require 1000 GJ more energy than that consumed by base case.

3.2 Electricity Production Efficiency (EPE)

Electricity Production Efficiency is calculated by summing the energy produced by a generating system over its lifetime (E_{gen} (lifetime)), and dividing it by the sum of the energy inputs required to manufacture (E_{mat} + E_{fab}), install, operate and maintain (E_{iom}, which is equal to E_{inst} +(module lifetime)*($E_{o\&m}$/yr)), and dispose of or reclaim it at the end of its lifetime (E_{elm}), using **Eq. (2)**. E_{iom} and E_{elm} are assumed to be zero for this analysis; actually both are likely to be small numbers over PV-system's lifetime (Lewis and Keoleian 1997).

$$Electric.Product.Effic. = \frac{E_{gen}(lifetime)}{E_{mat} + E_{fab} + E_{iom} + E_{elm}} \quad (2)$$

Electricity production efficiency is presented as a ratio. A system that generates more energy than is required to produce, would have an electricity production efficiency greater than unity and could be considered to be a sustainable system. Electricity production efficiency is a powerful metric for comparing photovoltaic technology with other systems for generating electricity because it puts all systems on an equivalent basis. To meet a definition of sustainability, an electricity production efficiency greater than unity is necessary: this enables the device to produce sufficient energy over its lifetime to at least reproduce itself. The conventional power systems have most of the times an electricity production efficiency (EPE) much lower than unity. For example the current United States electricity grid efficiency is 0.32.

In the present study, the EPE of the Diesel power station, through which island Nisyros is electrified, was not calculated, because the aim of the study was not to analyze the life cycle of this system.

In all cases studied, EPE was found greater than 1, which is essential for sustainable energy systems. KC-60 case has the lowest EPE followed by base case and improved case while the largest EPE is found in forward case.

The difference between base and improved case is enormous and shows that soon PV-systems will be a very efficient solution for electricity production. Finally, the fact that the lifespan of PV-system in forward case extends to 50 years results to a bigger EPE (about 9.5).

3.3 Net energy flow

The highest negative energy flow during the production of PV-systems is observed in base case. In improved case, there is a sufficient improvement with a drastical decrease of the negative energy flow. The most efficient net energy flow curve

can be seen in forward case, which will be in production in 10 years time. The produced energy during PV-system's lifespan is about 10 times greater than the energy required for the manufacture of the whole system. In KC-60 case, the curve presents similar characteristics with those of base case.

4 Conclusions

EPBT and EPE results indicate PV-systems' great potential in producing electricity using limited resources during the several steps of their life cycle. Moving gradually from base case or present situation to forward case which is nearly 10 years away, PV-systems will improve in their EPBT and EPE indicators making solar cell technology an important source of producing electricity and covering the increased needs of the world in energy.

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LCA of Multicrystalline Silicon Phtovoltaic Systems

Part 2: Application on an Island Economy

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Abstract

Aim, Scope and Background. The environmental and energy parameters of Photovoltaic systems play a very important role when compared to conventional power systems. In the present paper, a typical PV-system is analyzed to its elements and an assessment of the material and energy requirements during the production procedures is attempted. An LCA is being performed on the system of production of photovoltaics.

Main Features. A complete and accurate identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed. The emissions analysis is extended to the production of the primary energy carriers. This allows having a complete picture of the life cycle of all the PV-components described in the present study.

Methods and Tools. In order to obtain concrete results from this study, the specific working tool used is the Eco-Indicator '95 as being reliable and has been widely applied within LCA community A process that relates inventory information with relevant concerns about natural resource usage and potential effects of environmental loadings is attempted.

Conlusions. The analysis of all previous impact categories has shown that large-scale PV-systems have many advantages in comparison with a conventional power system (e.g. diesel power station) in electricity production. As a matter of fact, PV-systems become part of the environment and the ecosystems from the moment of their installation. Burdens are released from the PV-systems only during their manufacturing procedures.

Recommendation. Technological improvements need to be done in the manufacture of BOS-components which consume during their life cycle almost equal amounts of energy as the photovoltaic modules.

Keywords: Eco-indicators; energy pay-backtime (EPE); mc-silicon solar cells; multicrystalline silicon photovoltaic systems; PV-systems; silicon; solar cells; threshold limit values